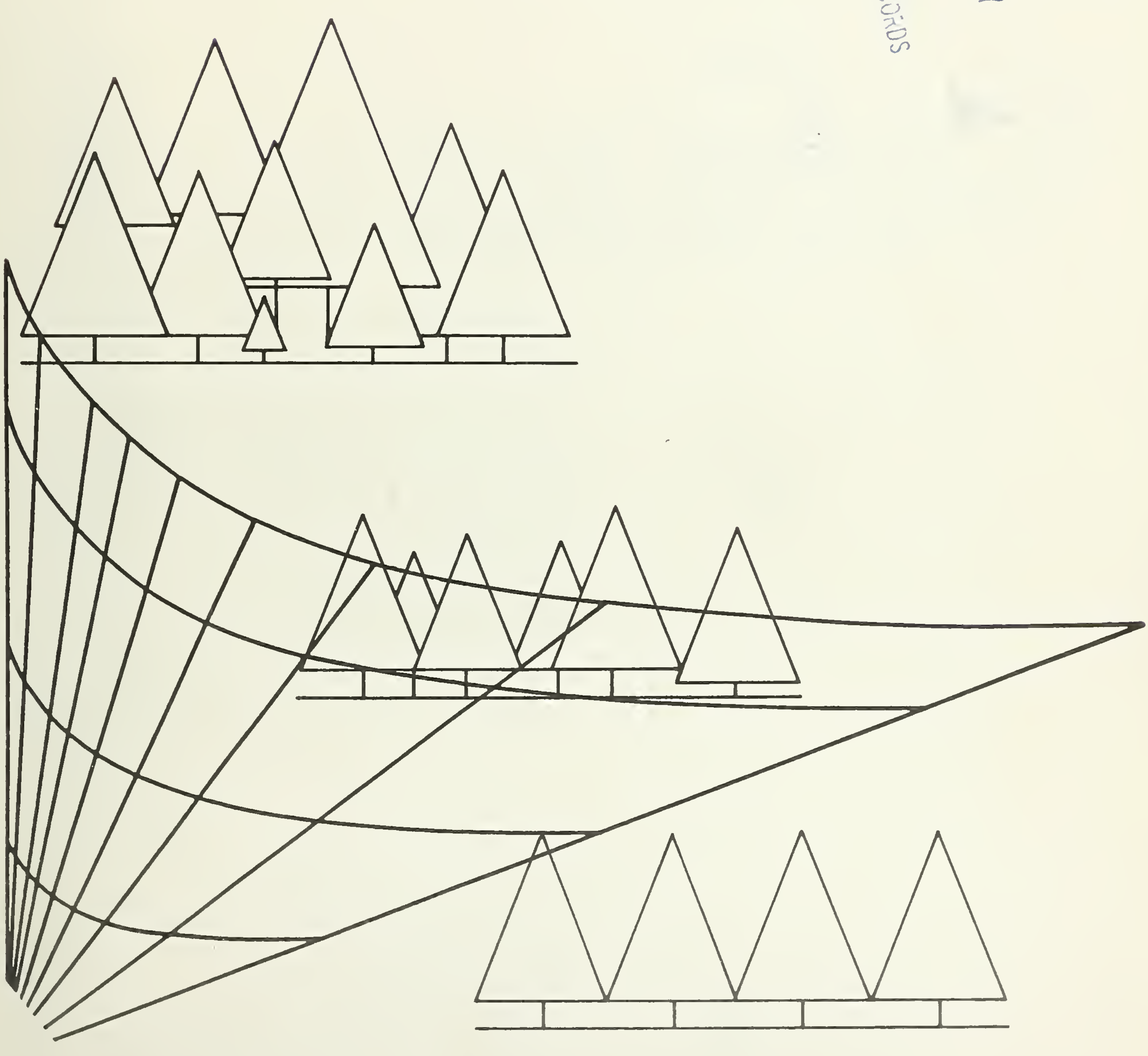
United States
Department of
Agriculture

Forest
Service

General
Technical
Report WO-44

Forest Stand Density and Stocking: Concepts, Terms, and The Use of Stocking Guides



Introduction

In this report we discuss the standardization of the concepts and terms of stocking and stand density. We also consider the use of stocking guides, especially the Gingrich guide.[1] Both the terminology and this guide have been adopted by the USDA Forest Service National Forest System and the Timber Management Research Staff, although research continues on new and better expressions of stand density.

The attempt to standardize stocking has long been a source of confusion and controversy among foresters, despite efforts to clarify the situation (Bickford and others 1957). Curtis (1970) identified basic relationships among a number of stand density measures, and his analysis unified the interpretation of many of these measures. MacLean (1979) made further distinctions and clarifications in terminology as applied to the Pacific Northwest Forest Survey. All these were admirable attempts to bring some meaningful criteria into the field.

[1]This name is incorrectly spelled "Ginrich" in the citation on page 7. In all other instances in this publication the correct spelling is used.

For we must remember that the development of standards in the matters of stocking and stand density are not of casual interest. They are vital to the performance of the work that we have undertaken. Such standards are implicitly demanded in the mandate that we have from Congress, in the National Forest Management Act of 1976, section 4(d)(1). ". . . It is the policy of Congress that all forested lands in the National Forest System shall be maintained in appropriate forest cover with species of trees, degree of stocking, rate of growth, and conditions of stand designed to secure the maximum benefits of multiple use sustained yield management in accordance with land management plans." (USDA FS 1983) The carrying out of this law requires the development, on a national level, of a standardized concept of stocking and a consistent interpretation, visualization, and application of stocking standards.

Definitions

To foster a common understanding and interpretation of stocking, it is first necessary to define the terminology and concepts used. The following definitions of stand density and stocking are recognized by the Society of American Foresters (1971):

> **Stand density**—A quantitative measure of tree stocking expressed either relatively as a coefficient, taking normal numbers, basal area, or volume (from yield table data) as unity; or absolutely, in terms of number of trees, total basal area, or total volume per unit area.
>
> **Stocking**—A loose term for the amount of anything on a given area, particularly in relation to what is considered the optimum.

Many foresters use these two terms interchangeably, but there are distinct differences. We will maintain consistency with these recognized definitions and will further clarify and interpret them. Also, in this publication, we are going to define other significant concepts and terms. Six of the most important are as follows:

- **Absolute stand density**—the absolute or measured quantity per unit area (that is, trees per acre or square feet per acre).
- **Management zone**—the area defined by the upper and lower bounds of acceptable relative densities in stands managed for a particular objective.
- **Reference level**—the absolute stand density that we would normally expect in a stand of given characteristics under some standard condition (usually average maximum competition, but may be no competition).
- **Relative stand density derived from average maximum competition**—the ratio (proportion or percent) of absolute stand density to the reference level based on average maximum competition.
- **Relative stand density derived from no competition**—the ratio (proportion or percent) of absolute stand density to the reference level based on no competition.
- **Stocking level**—a residual stand density, expressed as relative stand density, that achieves some management objective.

Stand density: some aspects

In the following discussion, we will assess density only in individual forest stands that have grown beyond the seedling-sapling stage. The term "stocking" can be used in a number of contexts. For example, stocking adequacy can be evaluated at several points in the life of a stand. The methods used during the early years are meant to evaluate the adequacy of the regeneration stocking. These methods differ from those used in later years when overstory stand density is evaluated. In this report we are concerned primarily with evaluating overstory density and developing standards for overstory stocking. (Those methods, however, that deal with regeneration stocking should always take care that the stand, as it matures, will ultimately fall within the desired management zone.)

It has long been recognized that intensive management of the forest resource can increase the yield of usable products over the rotation of the stand. Controlling stand density is a primary mechanism for controlling stand growth. In reviewing European thinning practices, Braathe (1957) stated:

> . . . In European thinnings, the best possible future development of the stand is the main principle. . . . This is best achieved by the free thinning method, which leaves a suitable number of the best trees as evenly spaced as possible over the area. . . . The height growth is little affected by thinning on good sites within the density interval used in practice. . . . On the other hand, diameter growth is greatly stimulated by thinnings, especially in the lower part of the trunk, producing larger dimensions in shorter time.

It is generally accepted that gross stand volume growth is fairly constant over a considerable range of stand densities, but net stand growth (gross growth less mortality) may decrease as stand density increases. Despite nearly constant gross stand volume increment, we thin to salvage the anticipated volume lost to mortality, and to put the volume increment onto fewer (and hopefully bigger and more desirable) trees in larger increments. Through intermediate thinnings we can control density and increase the total return from the stand over the rotation. When thinning, the question is how much material should be removed and how much should remain. Establishing stocking standards is an attempt to answer that question and to help the manager make sound decisions about treating the stand.

In a simplistic conception of the impact of stand density on growth, there are finite amounts of resources available in any given area for tree growth. If we start with a single tree on a plot, that tree would have all of the resources it could use, and excess resources would be available for other vegetation. We could add additional trees to the plot (increasing the stand density), and each would have all the resources it could use. But as the number of trees on the plot increases, inter-tree competition begins, and eventually a point is reached where all resources for growth are used. This is the point of full site utilization. As the number of trees on the plot further increases, the competition among the trees for light, moisture, and nutrients also increases.

Growth of individual trees in open stands will be at a maximum (within the limits imposed by other factors); however, total stand growth will be less than maximum. Stand growth increases with increasing numbers of trees, but at a decreasing rate since the growth of individual trees is reduced by increasing competition among trees. Above the point of full site utilization, growth of individual trees decreases as stand density increases, while total gross stand growth remains nearly constant. Mortality also increases as stand density increases because some individual trees would no longer have the minimum amount of resources required to survive.

When thinning, we manipulate stand density to capitalize on these growth responses. The primary objectives of thinning are to (1) salvage the material that otherwise would have died, thereby increasing total yields over the rotation; (2) increase the growth rate on individual trees selected to be retained; (3) improve quality and species composition; and (4) maintain stand health.

Stocking levels are the recommended residual relative stand densities that capitalize on these responses to best meet a specific management objective. (Management objectives will be discussed in more detail in a later section of this publication.)

Absolute stand density for stands of the same age, species composition, structure, and site is meaningful for purposes of comparison. When any or all of these stand characteristics change, comparison of absolute stand density becomes less meaningful. For example, it is a natural tendency for the basal area per unit area to increase and the number of trees per unit area to decrease as the stand grows older. Since these absolute measures change over time, meaningful comparisons among stands must include some measure of average tree size or stage of stand development.

The concept of relative stand density has been developed to provide meaningful comparisons among stands that differ in average tree size, age, site, and associated characteristics. Relative stand density is the ratio of the measured absolute density of a given stand to some reference level specific to that forest type. It describes the "degree of crowding" in the stand. When the evaluation of two stands results in the same relative stand density, they can be thought of as being at the same degree of crowding, even though they may differ in age, stand size, or species composition. This ability to measure and compare the degree of crowding is extremely valuable.

Stand density: reference levels

Two reference levels to measure stand density have been widely used. These levels must be determined biologically; and, as Curtis (1971) describes them, they may be either a level of average maximum competition or a level of no competition. The former is the more common and probably the more useful reference level. Note that some writers have used the biological maximum; this defines the extreme upper limit of density and is distinct from the average of many high-density stands. Average maximum competition is based on the absolute density observed in undisturbed stands of the same type and size, often referred to as "normal" stands in older American yield tables. The A-level in Gingrich's (1967) oak stocking guide and the maximum density lines of Reineke (1933) and Drew and Flewelling (1979) are examples of reference levels based on average maximum competition or an estimated upper limit of competition proportional to this average maximum. Measures such as Chisman and Schumacher's (1940) tree-area ratio, Reineke's (1933) stand density index, Curtis' (1982) RD, and Drew and Flewelling's (1977, 1979) relative density measure express stand density relative to such maximum density levels for stands of the same diameter (the most common measure) or some other measure of stand development.

The "no competition" reference level, 100 crown competition factor (100 CCF), is based on the observed relationship between crown area and diameter at breast height (d.b.h.) of open-grown trees. Crown width and d.b.h. are measured on trees that have developed without competition. The reference level is then defined by the number per unit area (acre or hectare) of such trees of a given diameter for which the sum of predicted crown areas is one unit area (acre or hectare). This is the point of crown closure of a hypothetical stand of uniformly distributed trees of the same diameter, with crown areas equal to those of open-grown trees of this diameter. The B-level line of the oak stocking guide, as developed from the crown competition factor (Krajicek et al. 1961), is an example of a reference level based on such a hypothetical stand. The "no competition" reference level is particularly useful in forest types where factors other than light are limiting, and the closed forest condition often used to identify stands where average maximum competition cannot often be found.

The choice of a reference level is critical, regardless of the standard of competition used as reference, because stocking levels are expressed in terms of that standard. A reference level would be unity or 100 percent, since it is what we expect in natural undisturbed stands. The crowding (or density) of any stand can be expressed in relation to the reference level as relative stand density, as a proportion or percent.

Because, in the past, there have been two reference levels from which relative density could be calculated, the definition of relative density may often be ambiguous. The reference level used should be specified. Since the most common and useful reference level is average maximum competition, we use the unqualified term "relative density" to denote stand density relative to average maximum competition. If the reference level used is "no competition," this should be stated explicitly. Only one reference level should be defined for a forest type.

Stocking levels and management objectives

Stocking level implies a management objective. This is distinct from stand density. A stocking level is the residual relative stand density that satisfies a management objective, and stocking is expressed as relative stand density. For example, optimum stand volume production may occur at a stocking level that is 60 percent of the average maximum competition reference level, or at a relative stand density of 60 percent.

Stocking levels that satisfy individual management objectives can be distinctly different; however, they are all expressed as relative stand density. When stand density is manipulated, the observed biological responses are the basis for defining a number of residual density levels. These levels include, but are not limited to, the levels that achieve:

- Maximum d.b.h. growth of individual trees.
- Maximum volume (or basal area) growth of stands.
- Maximum development of regeneration.
- Maximum development of understory wildlife food.
- Maximum seed production.
- Minimum or acceptable levels of windthrow.
- Minimum or acceptable levels of damage by insects and diseases.
- Minimum or acceptable bole degrade.

Two considerations are important in making an appropriate management decision: the biological response of the stand to a treatment and the economic factors. Biologically, undisturbed stands show a consistent pattern of development and tend to respond to a given treatment in a consistent way. Economically, the viability of a treatment depends on accessibility, markets, utilization standards, and other exogenous variables. The economic conditions, particularly markets, are by nature dynamic—what is true today might not be tomorrow. Appropriate management strategies are determined from the biological development and responses as constrained by the economic realities.

Any number of stocking levels can be established, each satisfying one or more management goals. The establishment of stocking levels should have long-term research support, and as research results accumulate, these stocking levels can be displayed more accurately on the guides that are drawn up.

Although an optimal residual density may be defined, strict maintenance of that level would require continuous cutting. There is a practical limit to the frequency of cutting in a stand, and it is based on economic returns. Generally, there would be a lower density limit below which stand production suffers, and an upper limit above which stand vigor deteriorates. As a result, a range of residual relative densities is implied as being acceptable. This range can be thought of as the management zone.

Use of stocking guides

Stocking guides have been developed for most of the major forest types and species in North America. Many of these guides express stand density as easily derived field estimates of the horizontal dimensions of a stand (that is, number of trees and/or basal area per unit area). Standardization of definitions associated with these guides, and of the format in which they are presented, is desirable in order to ensure a common understanding and interpretation of information, regardless of species type.

Several formats for such guides were exaamined, including those showing growing-stock levels for ponderosa pine (Myers 1967), natural stand relationships in Douglas-fir (Reukema and Bruce 1977), and stocking charts for eastern hardwoods (Gingrich 1967, Roach 1977, Leak et al. 1969). The displays drawn on these formats are founded on equations based on growing space requirements. Curtis (1970 and 1971) pointed out the functional relationships among them.

The important underlying concept for all of these guides is that a site has a biologic density potential. When a given stand is compared to this reference potential, the result is a measure of relative stand density. Regardless of the formulation used, the end result is a measure of crowding.

The Gingrich guide

Guides meant to express stocking levels have ranged from a simple plotting of number of trees or basal area by stand size to transformed scales and multiple dimensions. An approach developed by Gingrich (1967) has been used widely to show stand characteristics. This Gingrich guide has been adopted as the National Forest system's standard for stocking guides because of its simplicity and ease of use.

Some guides use only basal area or number of trees to show density. Gingrich's design uses both and because of this, information from other guides that use either basal area or number of trees can be transferred to this one format. The design of the Gingrich guide also aids in visualizing the dynamics of stand growth and the interactions of basal area and number of trees as a stand matures.

Gingrich's guide displays the stand basal area, the number of trees, and the quadratic mean diameter. These parameters are mathematically related and specification of any two implies the third. Both basal area per unit area (or the equivalent, sum of diameters squared times a constant) and number of trees per unit area are easily derived from a field cruise. The quadratic mean diameter (or the diameter of the tree of average basal area) is used as a measure of stand size. The mathematically derived interrelationships between them are shown in figure 1, the recommended background chart on which all the stocking levels can be plotted. Stocking guides that plot only two of these parameters (such as number of trees by stand size or basal area by stand size) can easily have their information transferred to this more comprehensive design. The basic form of the chart can be developed and used for any tree species or forest type. Of course, the reference level and stocking levels fitted to the chart will be specific to the species, plant community, forest type, habitat type, and management objectives.

Because of the need of some organizations for metric equivalents, stocking guides should be developed with both English and

metric units of measure. (To avoid confusion, this should be done through duplicate charts rather than the use of dual scales.) You may find it helpful to refer to a drawing of the Gingrich stocking guide (fig. 1) when reading the following sections.

Reference and stocking levels

It is not our purpose to standardize the techniques used in developing stocking guides. Nor do we recommend that there be only one reference level for all forest or habitat types, with stocking levels established on the basis of a single reference level. Rather, each forest type would have a unique reference level with appropriate stocking levels developed for specific economic conditions.

Much research has been directed toward establishing reference levels and stocking levels for many forest types, but additional research is needed on other forest types. Where the necessary information is available, developing a standardized stocking guide merely requires transferring the existing information to the format of the Gingrich guide. Where such information is lacking, considerable effort will be required. This should follow the recommended procedure that begins on page 7.

The major task in developing a stocking guide is establishing the reference level for stand density. A variety of techniques have been used. Curtis (1970) suggested that many of these techniques can be interpreted as expressions of average area requirements per tree under the specified conditions of the reference level. West (1982) also compared many of these measures and pointed out the advantages of some. Regardless of the methods used, the end result is the same—a measure of the expected basal area or number of trees for a stand of given size, composition, and structure under the specified condition of the reference level. Stands of similar size, composition, and structure can be compared to this level for a measure of relative density. Specific formulations of reference levels are detailed in the literature.

The information shown on the Gingrich (1967) stocking guide includes basal area, number of trees, and diameter of the tree of mean basal area. These parameters are easily derived from a field cruise, and relative stand density can then be read from the guide. The Gingrich stocking guide format as presented on this page is quick and easy to use.

An alternate and equivalent determination of relative stand density can be made. If the calculation of average maximum density is based on equations that indicate growing-space requirements, the contribution of each tree to relative stand density can be summed across the stand. Since the growing-space equations were developed for a specified reference condition, the calculation results in a measure of stand density relative to that reference level. The computation usually can be reduced to fairly simple equations easily evaluated for any given stand table.

Methods of determination based on either the chart or on the summation of growing-space requirements of individual trees, will result in an equivalent measure of relative stand density. A comparison with established stocking levels would then indicate the desirability of a thinning to better meet the management objective.

To develop a stocking level, a management objective must be determined. The recommended residual density (or stocking level) and the timing of stand treatments may differ for each objective. Developing a stocking level requires many long-term measure-

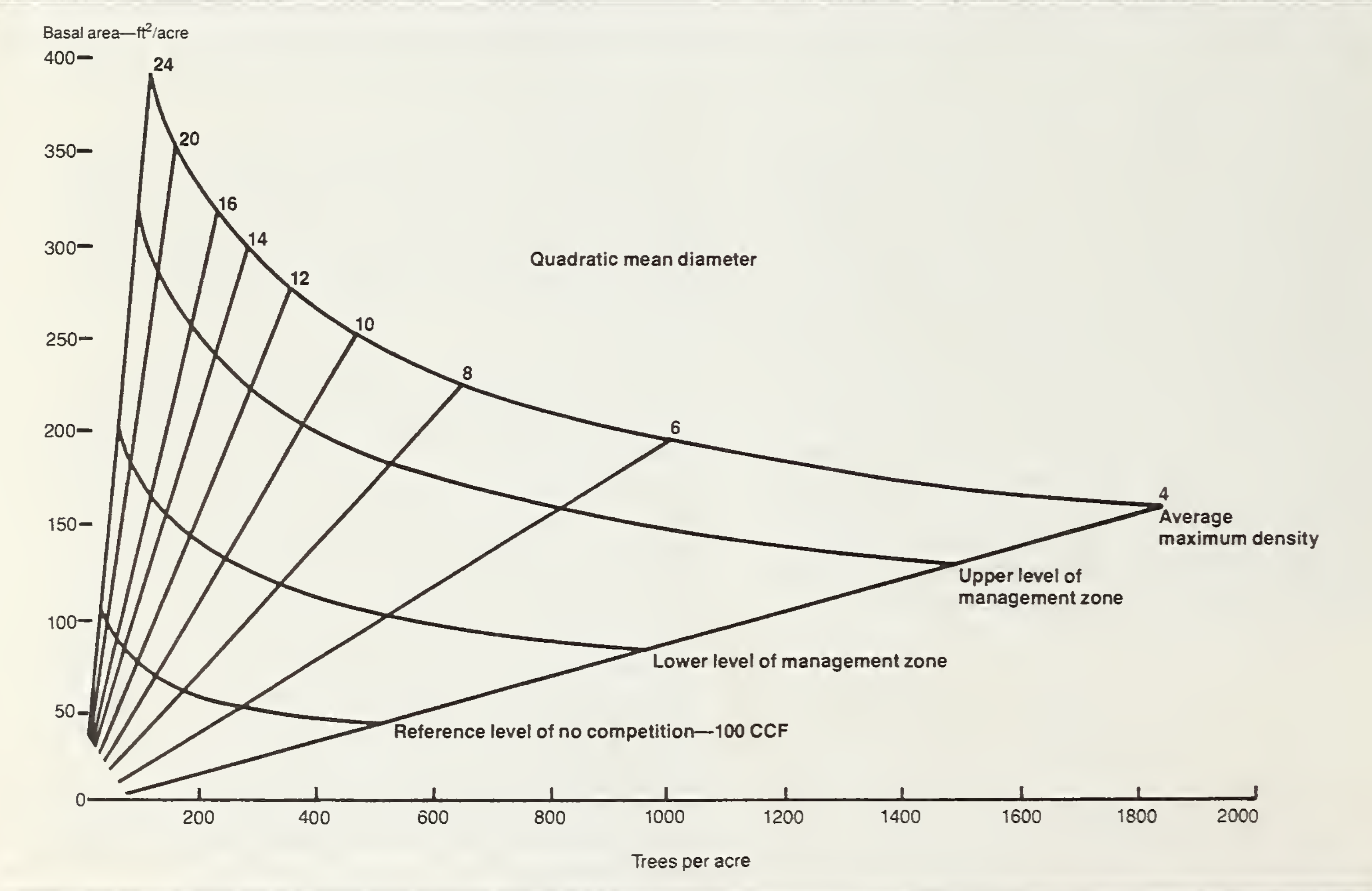


Figure 1—The Gingrich guide.

ments of biological responses to the manipulation of stand density. Stocking levels can be derived through simulation or direct analysis of the data, but either approach requires many experiments and trials in sample stands. In some forest types, detailed data are not available, and guides must be made on the basis of the best information available.

Procedure

The following procedure outlines the steps required in developing stocking guides. There is a great amount of work required to develop these guides; fortunately, some of this work may already be completed. Interim stocking guides are needed for species or types where data are not available. On-going consultation with and support from local research organizations such as universities or Forest Service research laboratories is important.

Step 1: Developing a reference level The reference level can be based on a standard of average maximum competition or no competition. The necessary data to develop this level depends on the standard that is selected. For a standard of no competition, crown width/d.b.h. equations often are available. If not, the basic data needed for each species are measurements of d.b.h. and crown width of trees grown in an open condition, and they must be collected over the entire range of diameters usually encountered. An equation of maximum crown area by diameter is developed from these data. Karjicek et al. (1961) outline these procedures in detail.

For a standard of average maximum competition, several methods already have been discussed. Growing-space allocation techniques are useful and result in reliable measures of stand density. The basic data needed are stand tables for all trees in a sample of stands. The stands selected for analysis should be undisturbed, even-aged, and natural; and should represent a range of age classes. Tree tallies should include all trees in the stand; trees as small as 1 inch d.b.h. should be counted where they make up a significant portion of the stand. Some data of this kind are available or can be adapted from reliable yield tables. An expression of growing-space requirements can then be developed. Mathematical procedures for deriving the necessary equations are found in Gingrich (1967), Chisman and Schumacher (1940), Curtis (1971), Reineke (1933), and West (1982).

Step 2: The stocking guide format After the data are obtained for the reference level, these data must be adapted into a form in which they can be used to determine the relative stand density of sampled stands. Developing a standard chart in the format of figure 1 entails solving the reference-level equation over a range of average stand sizes and plotting the solutions in the appropriate format. For types where this basic work already has been done but displayed differently, the data generally can be transformed easily into the standard chart format.

It also may be useful to fit (if necessary) the reference-level equations into a form in which they can be applied directly to sample stand data to derive the measure of relative stand density. Depending on the procedure used to decide on the reference level and the type of diameter distribution encountered in the particular forest type, one may need to modify the expression for average stand size. Gingrich (1967) and Rogers (1980) include an example of a type for which such a modification was required.

Step 3: Developing stocking levels Developing stocking levels is a long-term project. Biological growth responses to the manipulation of stand density must be monitored over long periods in plots controlled at various residual stand densities. In addition to volume responses, quality responses also can be monitored, particularly where high-quality sawtimber is a goal. Growth models developed from these data can be used to evaluate and select the residual densities that best meet the management objective for different economic conditions. Growth response also can be used to simulate alternative mangement strategies. Stocking levels developed for a specific forest type may indicate the treatments for similar forest types for which we have no stocking guides.

Stocking levels can be placed on the chart, stated mathematically, or stated narratively. For example, maximum volume production might occur at a known, specific residual relative density; this may be dependent on variables such as age stand or on previous management practices.

Step 4: Drawing up the stocking guide Each stocking guide should be drawn up in the Gingrich format and should include notations as to the origins of its data. The following information should be included:

- Species composition or forest type and geographic area of applicability.
- Definitions of the reference standard (as one of average maximum competition or some other standard).
- Equations for the reference level where available; sources of data and procedures of analysis should be documented.
- Placement of the upper and lower stocking levels for the specified management objective, and the management zone between. The management objective should be stated explicitly.

Step 5: Using the guides Comparing the actual relative density to the recommended relative density may imply an opportunity for silvicultural treatment. Stocking levels show stand densities that theoretically optimize some management objective (that is, volume or quality production under specific economic constraints), but they say nothing about the feasibility or operability of the treatment. Professional judgment still must be exercised when the implications of that judgment have become clear.

As was pointed out by Leak (1981), we must continue to evaluate the recommended stocking levels to see if they satisfy the desired management objective. Not meeting the objective does not destroy the usefulness of the entire concept, but it does suggest that refinements are needed in the stocking level or the recommended relative stand density. It is only through such evaluations that the stocking guides can be improved.

Literature Cited

Bickford, C. Allen and others. Stocking, normality, and measurement of stand density. Journal of Forestry. 55: 99–104; 1957.

Braathe, Peder. Thinnings in even-aged stands: A summary of European literature. Fredericton, NB: University of New Brunswick; 1957; Univ. New Brunswick Bull., 92 p.

Chisman, H. H.; Schumacher, F. X. On the tree-area ratio and certain of its applications. Journal of Forestry. 38: 311–317; 1940.

Curtis, Robert O. Stand density measures: An interpretation. Forest Science. 16: 403–414; 1970.

Curtis, Robert O. A tree area power function and related stand density measures for Douglas-fir. Forest Science. 17: 146–159; 1971.

Curtis, Robert O. A simple index of stand density for Douglas-fir. Forest Science. 38: 92–94; 1982.

Drew, T. John; Flewelling, James W. Some recent Japanese theories of yield-density relationships and their application to Monterey pine plantations. Forest Science. 23: 517–534; 1977.

Drew, T. John; Flewelling, James W. Stand density management: an alternative approach and its application to Douglas-fir plantations. Forest Science. 25: 518–532; 1979.

Ginrich [Gingrich], Samuel F. Measuring and evaluating stocking and stand density in upland hardwood forests in the central states. Forest Science. 13: 38–53; 1967.

Krajicek, John E.; Brinkman, Kenneth A.; Gingrich, Samuel F. Crown competition—a measure of density. Forest Science. 7: 35–42; 1961.

Leak, William B. Do stocking guides in the Eastern United States relate to stand growth? Journal of Forestry. 79: 661–664; 1981.

Leak, William B.; Solomon, Dale S.; Filip, Stanley M. A silvicultural guide for northern hardwoods in the Northeast. Res. Pap. NE–143. Upper Darby, PA: U.S. Department of Agriculture, Forest Service, Northeastern Forest Experiment Station; 1969. 34 p.

MacLean, Colin D. Relative density: the key to stocking assessment in regional analysis—a forest survey viewpoint. Gen. Tech. Rep. PNW–78. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station; 1979. 5 p.

Myers, Clifford A. Growing stock levels in even-aged ponderosa pine. Res. Pap. RM–33. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station; 1967. 8 p.

Reineke, L. H. Perfecting a stand-density index for even-aged forests. Journal of Agricultural Research. 46: 627–638; 1933.

Reukema, Donald L.; Bruce, David. Effects of thinning on yield of Douglas-fir: concepts and some estimates obtained by simulation. Gen. Tech. Rep. PNW–58. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station; 1977. 36 p.

Roach, Benjamin A. A stocking guide for Allegheny hardwoods and its use in controlling intermediate cuttings. Res. Pap. NE–373. Broomall, PA: U.S. Department of Agriculture, Forest Service, Northeastern Forest Experiment Station; 1977. 30 p.

Rogers, Robert. Evaluating stocking in upland central hardwood forests using metric measurements. Res. Pap. NC–187. St. Paul, MN: U.S. Department of Agriculture, Forest Service, North Central Forest Experiment Station; 1980. 5 p.

Society of American Foresters. Terminology of forest science, technology practice and products. Ford-Robertson, F.C., ed. Washington, DC: Society of American Foresters; 1971. 345 p.

U.S. Department of Agriculture, Forest Service. The principal laws relating to Forest Service activities. Agric. Handb. 453. Washington, DC: U.S. Department of Agriculture; (rev.) 1983. p. 441–460.

West, P. W. Comparison of stand density measures in even-aged regrowth eucalypt forest of southern Tasmania. Canadian Journal of Forest Research. 13: 22–31; 1982.